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## The anticharmed exotic baryon $\Theta_c$ and its relatives

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### Abstract

Motivated by the recent discovery of the exotic  $S = +1$  narrow baryon resonance  $\Theta^+$  at 1540 MeV, with quark content  $uud d\bar{s}$ , we conjecture the existence of its anti-charmed analogue  $\Theta_c$  with quark content  $uudd\bar{c}$ , and compute its likely properties. We rely on the recently constructed model of a novel kind of a pentaquark with an unusual color structure which provides a good approximation to the  $\Theta^+$  mass. We expect that  $\Theta_c$  is an isosinglet with  $J^P = \frac{1}{2}^+$  and estimate its mass at  $2985 \pm 50$  MeV. We also discuss another possible exotic baryon resonance containing heavy quarks, the  $\Theta_b^+$ , a  $uudd\bar{b}$  state, and estimate  $m_{\Theta_b^+} = 6398 \pm 50$  MeV. These states should appear as unexpectedly narrow peaks in  $D^-p$ ,  $\bar{D}^0n$ ,  $B^0p$  and  $B^+n$  mass distributions.

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## I. INTRODUCTION

The recent experimental discovery of an exotic 5-quark  $KN$  resonance [1–3],  $\Theta^+$  with  $S = +1$ , a mass of 1540 MeV and a very small width  $\sim 20$  MeV opens up the possibility that other similar exotic baryon resonances might exist.

The simplest quark configuration with the quantum numbers of the  $\Theta^+$  is  $uudd\bar{s}$ , with the light  $u$  and  $d$  quark likely coupled to an isosinglet. In a recent paper [4] we proposed an interpretation of the  $\Theta^+$  as  $uudd\bar{s}$  pentaquark consisting of an  $I = 0$  color antitriplet  $ud$  diquark coupled to an  $I = 0$  color triplet  $uds$  triquark, with one unit of relative orbital angular momentum between the two clusters. This unusual color structure turns out to minimize the hyperfine interaction of the color magnetic moments of the constituents. The resulting tri-diquark has  $I = 0$  and  $J^P = 1/2^+$ , in accordance with expectations based on the Skyrme model [5,6]. A rough estimate of the mass in [4] yields 1592 MeV, about 3% off the experimental value.

There is nothing in QCD that prevents the existence of states with more than 3 quarks, or mesons with additional quarks, on top of a quark and an antiquark. Yet, the spectacular phenomenological success of the quark model based on 3-quark baryons and quark-antiquark mesons made it almost a dogma that other, “exotic” states do not exist. Now, that the  $\Theta^+$  has been discovered experimentally, it is clear that this dogma needs a deep revision.

Any five-quark explanation of the  $\Theta^+$  should have the four quarks  $uudd$  coupled to isospin zero and an additional heavier antiquark. This immediately raises the question of the flavor of the antiquark. If any  $(uudd\bar{s})$  model is good for a strange antiquark, why not also a similar  $(uudd\bar{Q})$  model with any heavy antiquark  $Q$  like charmed or bottom? QCD tells us that the only difference QCD sees between these different flavors is their mass. So it is reasonable to look for a narrow resonance also in  $D^-p$ ,  $\bar{D}^0n$  or  $B^0p$ ,  $B^+n$ . These should appear as unexpectedly narrow peaks in mass distributions.

In this work we focus on the possibility that such exotic baryons do exist, and compute their properties, using the model constructed in Ref. [4].

## II. THE DIQUARK-TRIQUARK MODEL

Most quark model treatments of multiquark spectroscopy use the color-magnetic short-range hyperfine interaction [7] as the dominant mechanism for possible binding. The application of this interaction by Jaffe [8] to treat the exotic color configurations not found in normal hadrons used a color-spin  $SU(6)$  algebra in which the hyperfine interaction between two quarks denoted by  $i$  and  $j$  is written as

$$V_{hyp} = -V(\vec{\lambda}_i \cdot \vec{\lambda}_j)(\vec{\sigma}_i \cdot \vec{\sigma}_j) \quad (2.1)$$

where  $\vec{\lambda}$  and  $\vec{\sigma}$  denote the generators of  $SU(3)_c$  and the Pauli spin operators, respectively. Jaffe has used the sign and magnitude of the  $\Delta$ -nucleon mass splitting as input for the sign and strength of the hyperfine interaction. The quark-quark interaction (2.1) is seen to be attractive in states symmetric in color and spin where  $(\vec{\lambda}_i \cdot \vec{\lambda}_j)$  and  $(\vec{\sigma}_i \cdot \vec{\sigma}_j)$  have the same sign and repulsive in antisymmetric states where they have opposite signs. This then leads to the "flavor-antisymmetry" principle [9]: the Pauli principle forces two identical fermions at short distances to be in a state that is antisymmetric in spin and color where the hyperfine interaction is repulsive. Thus the hyperfine interaction is always repulsive between two quarks of the same flavor, such as the like-flavor  $uu$  and  $dd$  pairs in the nucleon or pentaquark.

This flavor antisymmetry suggests that the bag or single-cluster models commonly used to treat normal hadrons may not be adequate for multiquark systems. In such a state with identical pair correlations for all pairs in the system all same-flavor quark pairs are necessarily in a higher-energy configuration due to the repulsive nature of their hyperfine interaction. The  $uudd\bar{s}$  pentaquark is really a complicated five-body system where the optimum wave function to give minimum color-magnetic energy can require flavor-dependent spatial pair correlations for different pairs in the system; e.g. that keep the like-flavor  $uu$  and  $dd$  pairs apart, while minimizing the distance and optimizing the color couplings within the other pairs. This is the physical basis for the success of the diquark-triquark model [4]. An even more complicated spatial configuration might well do better.

To see a simple picture of the model constructed in Ref. [4] take a  $K^+$  and a neutron and put them just far enough apart so that they are out of the range of the very short range Fermi color hyperfine interaction. Now take one of the  $d$ -quarks in the neutron and move it over to the kaon and recouple the color and spin to optimize the hyperfine interaction.

Moving the quark a distance from a point  $r_1$  to a point  $r_2$  while doing nothing to the kaon requires an energy in the potential model of the neutron of  $V(r_2) - V(r_1)$ , where  $V$  is the confining potential; e.g. Coulomb + linear. The energy is in the color electric field that has been created between  $r_1$  and  $r_2$ . This distance costs color electric energy. Recoupling the color and spins of the triquark gains hyperfine energy. But because the triquark is a color-electric triplet like the quark, the recoupling does not change the color electric field in the approximation where the spatial extension of the triquark is neglected.

The change in color-electric energy can also be described in the approximation of a point triquark and point diquark by solving the Schroedinger equation for a quark-antiquark pair in the confinement potential. One has to balance the gain in hyperfine energy with the excitation energy of the relative diquark-triquark system in the confinement potential. The rough calculation in Ref. [4] suggests that this tradeoff between the hyperfine and the confining interaction reproduces the measured mass of the  $\Theta^+$ .

In this picture we can replace the strange antiquark by a charmed antiquark and get a narrow resonance in  $D^-$ -proton scattering. This might be seen by FOCUS by checking the invariant mass distribution of  $D^-$ -proton, to see whether there may be a narrow peak like the  $\Theta^+$ . This possibility is discussed in detail in the next section.

### III. EXOTIC BARYONS WITH $\bar{c}$ OR $\bar{b}$ INSTEAD OF $\bar{s}$

The detailed Skyrme model prediction for the anti-strange pentaquark [6] has now been beautifully confirmed by the data [1–3]. However, the exotic baryons in which the  $\bar{s}$  is replaced by a heavier antiquark cannot be treated within the Skyrme model approach of Ref. [6], in which the strange antiquark is in the same  $SU(3)_f$  multiplet as  $u$  and  $d$ , and

symmetry breaking by quark mass differences is treated as a first-order perturbation. This approach may be fine for the  $s$  quarks, but it not valid for heavier quarks such as  $c$  and  $b$ .

In contrast, the explicit model in Ref. [4] is easily generalized to include any mass for the antiquark. This mass appears only in the hyperfine interaction between the antiquark and the  $ud$  pair in the triquark, with a coefficient inversely proportional to the antiquark mass. All that is necessary to consider an antiquark of any flavor is to adjust this coefficient to the appropriate inverse quark mass.

Ref. [4] treats the hyperfine interactions in the diquark-triquark model in the  $SU(3)$  limit; i.e. with the mass of the strange antiquark equal to the masses of the  $u$  and  $d$  quark. The necessary generalization to include any antiquark flavor and mass is easily incorporated by separating the quark-quark and quark-antiquark interaction and changing the coefficient of the quark-antiquark interaction to correspond to the correct antiquark mass.

To show explicitly how the results of Ref. [4] can be generalized, we first review in detail the calculation leading to their result.

We use the general form of the color-spin hyperfine interaction [8] for systems containing both quarks and antiquarks:

$$V = (v/2)[\bar{C}(tot) - 2\bar{C}(Q) - 2\bar{C}(\bar{Q}) + 16N] \quad (3.1)$$

where  $V$  is the total hyperfine contribution to the mass of the system, and  $v$  is a parameter defining the strength of the interaction, normalized by computing the value of  $V$  for the nucleon and the  $\Delta$ , and equating it with the experimental value of the  $\Delta$ -nucleon mass splitting,

$$M(\Delta) - M(N) = V(\Delta) - V(N) = 16v, \quad (3.2)$$

$\bar{C}(tot)$ ,  $\bar{C}(Q)$  and  $\bar{C}(\bar{Q})$  denote respectively the values for the whole system and for the subsystems of all the quarks and all the antiquarks in the system of the following linear combination of Casimir operators

$$\bar{C} = C_6 - C_3 - (8/3)S(S+1) \quad (3.3)$$

$C_6$  and  $C_3$  denote the eigenvalues of the Casimir operators of the  $SU(6)$  color-spin and  $SU(3)$  color groups respectively, and  $S$  and  $N$  denote the total spin and the number of quarks in the system.

The diquark, triquark and meson states are labeled in the conventional notation  $|D_6, D_3, S, N\rangle$  [14,15] where  $D_6$  and  $D_3$  denote the dimensions of the color-spin  $SU(6)$  and color  $SU(3)$  representations in which the multiquark states are classified, .

$$|\text{diquark}(S=1)\rangle = |(2q)_{21}^1\rangle = |\bar{2}1, 6, 1, 2\rangle \quad (3.4)$$

$$|\text{diquark}(S=0)\rangle = |(2q)_{21}^0\rangle = |\bar{2}1, \bar{3}, 0, 2\rangle \quad (3.5)$$

$$|\text{triquark}(S=1/2)\rangle = |(2q\bar{s})_{21}^{(1/2)}\rangle = |6, 3, 1/2, 3\rangle \quad (3.6)$$

$$|\text{meson}\rangle = |(q\bar{s})_1^0\rangle = |1, 1, 0, 2\rangle \quad (3.7)$$

Then

$$\bar{C}(2q)_{21}^1 = [(160/3) - (40/3) - (16/3)] = (104/3) \quad (3.8)$$

$$\bar{C}(q) = \bar{C}(\bar{s}) = [(70/3) - (16/3) - 2] = 16 \quad (3.9)$$

$$\bar{C}(q\bar{s})_1 = [(0)] = 0 \quad (3.10)$$

The interaction is easily evaluated for the diquark states (3.4-3.5) by substituting the eigenvalues of the Casimir operators [14,15]:

$$C_6(6) = (70/3) \quad (3.11)$$

$$C_6(21) = (160/3) \quad (3.12)$$

$$C_3(3) = (16/3) \quad (3.13)$$

$$C_3(6) = (40/3) \quad (3.14)$$

We then obtain

$$V(2q)_{21}^1 = -(v/2)[(160/3) - (40/3) - (16/3) - 32] = -(8/3)(v/2) \quad (3.15)$$

$$V(2q)_{21}^0 = -(v/2)[(160/3) - (16/3) - 32] = -(16)(v/2) \quad (3.16)$$

For the triquark and meson states we obtain

$$V(2q\bar{s})_{21}^1 = (v/2)[16 - 2(104/3) - 32 + 48] = -(112/3)(v/2) \quad (3.17)$$

$$V(q\bar{s})_0 = (v/2)[-64 + 32] = (-32)(v/2) \quad (3.18)$$

We now separate the contributions to the triquark hyperfine interaction(3.17) into the quark-quark and quark-antiquark contributions by noting that the hyperfine interaction in the diquark that is in the triquark is  $-(8/3)(v/2)$  , We can then write the generalized triquark hyperfine interaction for the case where the antiquark mass is  $m_Q$ .,

$$V(2q\bar{s})_{21}^1 = -(8/3)(v/2) - \zeta \cdot (104/3)(v/2) \quad (3.19)$$

where  $\zeta = m_u/m_Q$ . For the generalized meson,

$$V(q\bar{s})_0 = -\zeta \cdot (32)(v/2) \quad (3.20)$$

The hyperfine interaction in the diquark of our diquark-triquark model is equal to the hyperfine interaction in the nucleon.

$$V(N) = V(\Lambda) = V(2q)_{21}^0 = -8v$$

Thus the difference between the hyperfine interactions in the diquark-triquark system will differ from that in the kaon-nucleon system only by the difference between the triquark and the kaon.

$$V(2q\bar{s})_{21}^1 - V(q\bar{s})_0 = -(1 + \zeta) \cdot (4/3)v \quad (3.21)$$

$$[V(2q\bar{s})_{21}^1 + V(d_{21}^0)] - [V(q\bar{s})_0 + V(N)] = -\frac{1+\zeta}{12} \cdot [M(\Delta) - M(N)] \quad (3.22)$$

The hyperfine interaction is greater by  $(1 + \zeta) \cdot (1/12)[M(\Delta) - M(N)]$  for the diquark-triquark system than for the kaon nucleon system. This gives previous result [4] of  $-(8/3)v = -(1/6)(M_\Delta - M_N)$  for  $\zeta = 1$ . This result is obtained without any flavor symmetry assumption and holds for any mass antiquark.

### A. The anticharmed exotic baryon $\Theta_c = uudd\bar{c}$

We now apply this formalism to the specific case of the anticharmed exotic baryon  $\Theta_c$ , i.e. the  $uudd\bar{c}$  pentaquark. We use effective quark masses that fit the low-lying mass spectrum [4]:

$$m_u = m_d = 360 \text{ MeV}; \quad m_s = 540 \text{ MeV}; \quad m_c = 1710 \text{ MeV}; \quad m_b = 5050 \text{ MeV}. \quad (3.23)$$

from this we find a very rough estimate of the  $ud$  diquark and  $ud\bar{c}$  triquark effective masses

$$m_{ud} = 720 \text{ MeV}; \quad m_{ud\bar{c}} = 2430 \text{ MeV}, \quad (3.24)$$

so that the reduced mass for the relative motion of the  $ud$  diquark and  $ud\bar{c}$  triquark system is  $m_r(\{ud\}-\{ud\bar{c}\}) = 555 \text{ MeV}$ . This reduced mass is fairly close to the reduced mass of the  $c\bar{s}$  system used to describe the internal structure of the  $D_s$  spectrum,  $m_r(c\bar{s}) = 410 \text{ MeV}$ . The dependence of the excitation energy on the reduced mass is expected to be rather small, e.g. the  $\psi' - J/\psi$  splitting is 589 MeV vs. 563 MeV for  $\Upsilon' - \Upsilon$ . Using the proximity of reduced masses, we can obtain a rough estimate of the  $P$ -wave excitation energy in the  $\{ud\}-\{ud\bar{c}\}$  diquark-triquark system [4], using the relevant experimental information about the  $D_s$  system, [10–13]

$$\delta E^{P\text{-wave}} \approx 207 \text{ MeV}. \quad (3.25)$$

From eq. (3.22) we infer that without the  $P$ -wave excitation energy the  $\{ud\}-\{ud\bar{c}\}$  diquark-triquark mass is



$$m_{\{ud-ud\bar{c}\}}^0 = m_N + m_D - \frac{1}{12} (1 + \zeta_c) [M(\Delta) - M(N)] \approx 2778 \text{ MeV}. \quad (3.26)$$

where  $\zeta_c = m_u/m_c = 0.21$ . so that the total mass of the  $\{ud\}$ - $\{ud\bar{c}\}$  diquark-triquark is

$$M_{\Theta_c} \approx 2778 + 207 = 2985 \text{ MeV}. \quad (3.27)$$

Clearly, this is a rather rough estimate so it should be expected to hold to no more than to within 50 MeV, so we expect  $M_{\Theta_c} = 2985 \pm 50 \text{ MeV}$ . In Ref. [4] the same approach gave an estimate  $m_{\Theta^+} = 1592 \text{ MeV}$ , overshooting the experimental value by about 50 MeV, so it is quite possible that the estimate (3.27) might be overshooting a bit as well, but at this point we don't think the mass estimate is accurate enough to use the  $\Theta^+$  input to fine-tune the prediction.

Assuming flavor  $SU(3)$  symmetry, the general formula for the decay rate of a baryon  $B_1$  of mass  $M_1$  into a baryon  $B_2$  with mass  $M_2$ , plus an octet pseudoscalar meson  $\mathcal{P}$  of mass  $M_{\mathcal{P}}$  is given by [6]

$$\Gamma(B_1 \rightarrow B_2 + \mathcal{P}) = \frac{3G_0^2}{2\pi(M_2 + M_1)^2} |\vec{p}|^3 \frac{M_2}{M_1} \times \mathcal{C} \quad (3.28)$$

where  $|\vec{p}| = \sqrt{(M_1^2 - (M_2 + M_{\mathcal{P}})^2) \cdot (M_1^2 - (M_2 - M_{\mathcal{P}})^2)} / 2M_1$  is the momentum of the meson,  $G_0$  is the appropriate coupling constant (an analogue of  $g_{\pi NN}$ ) and  $\mathcal{C}$  is an  $SU(3)_f$  group-theoretical factor, depending on the flavor and spin quantum numbers of the initial and final state hadrons. Schematically,

$$\Gamma(B_1 \rightarrow B_2 + \mathcal{P}) = G_0^2 \times \mathcal{C} \times (\text{phase space}) \quad (3.29)$$

In [6] eq. (3.28) was shown to compare well with experiment for several well-measured decays of decuplet baryons, such as  $\Delta \rightarrow N\pi$ ,  $\Sigma^* \rightarrow \Lambda\pi$ , etc., assuming  $G_0 \approx 19$ , with values of  $\mathcal{C}$  which turned out to be between 1/15 and 1/5.

Next, for the decay  $\Theta^+ \rightarrow KN$ , it was assumed that  $G_0 \approx 9.5$  and  $\mathcal{C} \approx 1/5$ , yielding the prediction  $\Gamma(\Theta^+ \rightarrow KN) = 15 \text{ MeV}$ , which seems to be in good agreement with experiment [1–3]. On a qualitative level, the crucial observation is that the phase space for  $\Theta^+ \rightarrow KN$  is very small, so  $\Theta^+$  is narrow, even though  $G_0^2 \times \mathcal{C} \sim 20$ .

In order to obtain a very rough estimate of the width of the decay  $\Theta_c \rightarrow DN$ , we use eq. (3.28) with  $M_1 = M_{\Theta_c} = 2985$  MeV, as given by (3.27),  $M_2 = M_N$ ,  $M_P = M_D$ ,  $G_0 \sim 10$  and  $\mathcal{C} \sim 1/5$ . This yields

$$\Gamma(\Theta_c \rightarrow DN) \sim 21 \text{ MeV}. \quad (3.30)$$

Clearly, eq. (3.30) should be viewed only as indication of the expected width, probably no better than a factor of 2. On the face of it, this is for three reasons at least:

- (a) we do not know the value of the  $g_{\pi NN}$  analogue,  $g_{D\Theta_c N} = G_0$ ;
- (b) the group-theoretical factor  $C$  was originally derived for  $SU(3)_f$ ;
- (c) the phase space is very sensitive to mass differences, so a relatively small shift in  $\Theta_c$  mass can cause a significant shift in its width.

Still, the estimate (3.30) is probably in the right ball park, since  $g_{D\Theta_c N}$  is a meson-baryon-baryon coupling, so assuming  $g_{D\Theta_c N} \sim 10$  is not unreasonable. As for the group-theoretical factor  $\mathcal{C}$ , formally we can think of introducing (a very badly broken) flavor group  $SU(3)$  encompassing the  $u$ ,  $d$  and  $c$  quarks. The group-theoretical factor reflects the group structure with no mass dependence, so changing  $s$  to  $c$  should not affect it.

On a qualitative level, it is important to realize that the phase space for  $\Theta_c \rightarrow DN$  is small, so for a typical hadronic coupling and a typical group-theoretical factor we expect  $\Theta_c$  to be narrow.

### B. The exotic baryon $\Theta_b^+ = uudd\bar{b}$

The above discussion can now be repeated, this time replacing  $\bar{s}$  by  $\bar{b}$ . We expect the  $\Theta_b^+$  to have the same isospin and spin-parity as  $\Theta_c$ , i.e. an isosinglet with  $J^P = \frac{1}{2}^-$ .

The  $\Theta_b^+$  mass is estimated exactly as for  $\Theta_c$ , i.e. from eq. (3.23) we obtain a very rough estimate of the  $ud\bar{b}$  triquark effective mass,  $m_{ud\bar{b}} = 5770$  MeV, so that the reduced mass for the relative motion of the  $ud$  diquark and  $ud\bar{b}$  triquark system is  $m_r(\{ud\}-\{ud\bar{b}\}) = 640$  MeV. As in the  $\Theta_c$  case, without the  $P$ -wave excitation energy the  $\{ud\}$ - $\{ud\bar{b}\}$  diquark-triquark mass is

$$m_{\{ud-ud\bar{b}\}}^0 = m_N + m_B - \frac{1}{12} (1 + \zeta_b) [M(\Delta) - M(N)] \approx 6191 \text{ MeV}. \quad (3.31)$$

where  $\zeta_b = m_u/m_b = 0.07$ , so that the total mass of the  $\{ud\}$ - $\{ud\bar{b}\}$  diquark-triquark is

$$M_{\Theta_b^+} \approx m_{\{ud-ud\bar{b}\}}^0 + \delta E^{P\text{-}wave} = 6191 + 207 = 6398 \pm 50 \text{ MeV}. \quad (3.32)$$

In order to obtain a very rough estimate of the width of the decay  $\Theta_b^+ \rightarrow BN$ , we again use eq. (3.28) with  $M_1 = M_{\Theta_b^+} = 6398 \text{ MeV}$ , as given by (3.32),  $M_2 = M_N$ ,  $M_P = M_B$ ,  $G_0 \sim 10$  and  $\mathcal{C} \sim 1/5$ . This yields

$$\Gamma(\Theta_b^+ \rightarrow BN) \sim 4 \text{ MeV}. \quad (3.33)$$

Again, we repeat here all the caveats regarding the very rough nature of this estimate, as explained following the estimate of the  $\Theta_c$  width. On a qualitative level however, it seems quite likely that the  $\Theta_c$  width will indeed be substantially more narrow than the width of  $\Theta_c$ .

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## REFERENCES

- [1] T. Nakano *et al.* [LEPS Coll.], Phys. Rev. Lett. **91**(2003)012002, hep-ex/0301020.
- [2] V. V. Barmin *et al.* [DIANA Collaboration], hep-ex/0304040.
- [3] S. Stepanyan [CLAS Collaboration], hep-ex/0307018.
- [4] K. Karliner and H.J. Lipkin, hep-ph/0307243.

- [5] M. Chemtob, Nucl. Phys. B **256**, 600 (1985); M. Karliner and M. P. Mattis, Phys. Rev. D **34**, 1991 (1986); M. Praszalowicz in Proc. Cracow Workshop on Skyrmions and Anomalies, Mogilany, Poland, Feb 20-24, 1987, M. Jezabek, M. Praszalowicz, Eds., WORLD SCIENTIFIC, Singapore 1987, p. 112. H. Weigel, Eur. Phys. J. A **2**, 391 (1998) [arXiv:hep-ph/9804260].
- [6] D. Diakonov, V. Petrov and M.V. Polyakov, Z. Phys. A **359**(1997)305, hep-ph/9703373.
- [7] A. De Rujula, H. Georgi and S.L. Glashow, Phys. Rev. D **12** (1975) 147
- [8] R. L. Jaffe, Phys. Rev. Lett. **38**, (1977) 195
- [9] Harry J. Lipkin, Phys. Lett. B **70**, (1977) 113
- [10] B. Aubert *et al.* [BABAR Collaboration], hep-ex/0304021.
- [11] D. Besson, *et al.*, [CLEO Collaboration], hep-ex/0305017.
- [12] Tom Browder's talk on behalf of BELLE Collaboration at CIPANP 2003, May 19-24, 2003, NYC, [http://www.phys.hawaii.edu/~teb/dspi\\_nyc.pdf](http://www.phys.hawaii.edu/~teb/dspi_nyc.pdf).
- [13] K. Hagiwara *et al.* [Particle Data Group Collaboration], Phys. Rev. D **66**, 010001 (2002).
- [14] W. G. McKay and J. Patera, Tables of Dimensions, Indices, and Branching Rules for Representations of Simple Lie Algebras, (Marcel Dekker, New York, 1981) p. 98
- [15] H. Högaasen and P. Sorba, Nucl. Phys. B **145** (1978) 119